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Quantitative relationships between climate and magnetic susceptibility of soils on the Bačka Loess Plateau (Vojvodina, Serbia)

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ABSTRACT

Magnetic properties of soils formed in and on loess substrate and their relation to climate are of general interest in paleoclimate and pedological research. The loess-paleosol sequences (LPS) in the Vojvodina region (Serbia) have been the subject of intensive study. On the Bačka loess plateau (BLP), covering approximately 2500 km^2, six different soil types are observed. While the stratigraphy of the LPS has been investigated the relation between climatic factors and magnetic properties of surface soil have not yet been examined. In this study we analyze 50 samples of chernozem soils, which have been dominated by climatic factors during their formation. Previous studies have confirmed that the formation of magnetic properties in soils is related to climate, and especially rainfall, because of the response of hematite and goethite to different, climatically-driven regimes. The sensitivity of certain iron-bearing minerals to climate has also been documented in the literature. Climatic variables for the BLP were derived from six-decade national meteorological datasets. Low frequency magnetic susceptibility (χ) and frequency dependent magnetic susceptibility (χ_{fd}) were determined for each site and compared to the mean annual precipitation (MAP), mean annual temperature (MAT) and the De Martonne aridity index (I_{DM}). The meteorological variables were interpolated to sampling points by Kriging method in *ArcMap 10.1*. Our results suggest that values of χ and χ_{fd} both decrease from south to north and so does the precipitation. Thus, our work provides new evidence for the relationship between precipitation, temperature, aridity and magnetic properties of modern top soils. The obtained and analyzed data may help in the future to improve transfer functions of the relationship between magnetic susceptibility and climatic data.

1. Introduction

Across Vojvodina, in the northern region of Serbia, ~60% of the surface is covered by loess, with a maximum thickness of 55 m (Marković et al., 2008; 2015; Schmidt et al., 2010). Six major loess plateaus occur in the region (Marković et al., 2004a; Bokhorst et al., 2009), which contain some of the most complete European continental climate records (Marković et al., 2015 and reference therein). Our study focuses on the Bačka Loess Plateau (BLP), located in the southern Carpathian basin (Fig. 1). Loess plateaus in the southern Carpathian basin can be the relicts of once larger loess areas which have been dissected by the Danube and Tisza rivers and their tributaries (Popov et al., 2008). The exact source of this material is under debate (Buggle et al., 2008; Marković et al., 2015).

The BLP is located in the southeastern Danube River basin. Here, the Danube has several large tributaries - the Tisza, Sava, Mures, and Drava Rivers. These rivers drain the Alps, Carpathians, and Dinaric Alps, transporting large amounts of sediment. This BLP spans approximately 2500 km^2. Because of this relatively small area we have assumed a homogenous geochemical composition of its loess, which is the background sediment for development of chernozem soils. Research on the BLP is facilitated by large exposures of loess-paleosol sequences (LPS) in local brickyards such as at Crvenka, Sivac, Bačka Topola, Novo Orahovo, and Kula (Marković et al., 2014; Stevens et al., 2011; Zech et al., 2013; Sipos et al., 2016).

The role of climate as main controlling factor of loess-soil magnetic characteristics has been in the focus of research since the beginning of systematic studies of magnetic properties of soils formed in and on loess

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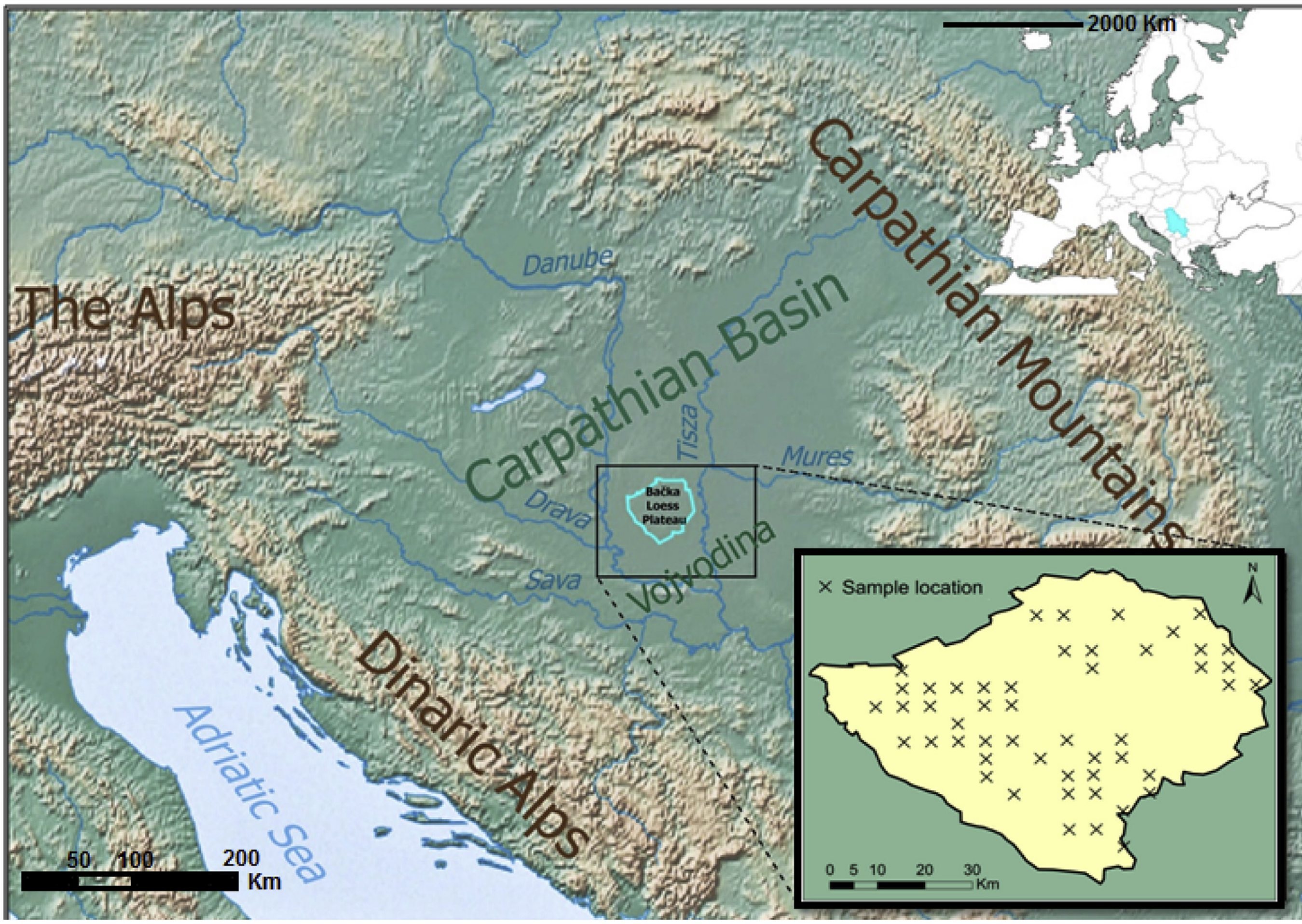

Fig. 1. Location of the Bačka Loess Plateau in the Carpathian Basin, Europe. The locations of soil samples examined in this study are marked as ' × '.

substrate (e.g. Maher, 2011). In this study, the low field magnetic susceptibility (χ) and frequency dependent magnetic susceptibility (χ_{fd}) were measured for the surface soils of the BLP, making it the first loess plateau in Serbia to be investigated in this way. With the exception of climate, the soil-forming factors are fairly uniform across the plateau. The soil parent materials are all loess of Holocene age; all sites are on uplands and have formed under grassland vegetation. Thus, climatic variability is the main factor that has led to variation in soil properties. The Holocene soils across the BLP generally correspond with Marine Oxygen Isotope Stage (MIS) 1 (Stevens et al., 2011). Using the Danube loess stratigraphy, this soil is labeled as S0 (Marković et al., 2015) which corresponds to the Chinese loess stratigraphic model (Kukla, 1987; Kukla and An, 1989).

The purpose of this study is to investigate the spatial relationships between temperature, precipitation and aridity, and the magnetic signal in the modern soils of the Bačka Loess Plateau. Magnetic properties of soil are sensitive environmental indicators which can be regarded as proxies for soil formation intensity (Maher, 1998). Magnetite and maghemite are the minerals that primarily control the magnetic signal enhancement that occurs during soil formation. Many factors can affect the value of χ and χ_{fd} in soils, e.g., the parent material (Maher, 1998; Wei et al., 2008), including mineralogy and magnetic grain size (Liu et al., 2013), precipitation, temperature (Barrón et al., 2003; Torrent et al., 2010; Guo et al., 2011; Song et al., 2014; Liu et al., 2017), evaporation (Orgeira and Compagnucci, 2006; Orgeira et al., 2011), weathering intensity (Marković et al., 2004b; Buggle et al., 2011), local factors such as crop burning, land-use, or pollution (Dearing et al., 1996), and the contributions of magnetotatic bacteria (Fassbinder et al., 1990; Maher and Thompson, 1995; Dearing et al., 1996), and Fe-reducing microorganisms (Lovley et al., 1987). The correlation between χ and climatic parameters has been investigated in the northern hemisphere in the past few decades in Mali, Egypt, Togo, Morocco (Balsam et al., 2011), China (Maher et al., 1994; Maher and Thompson, 1995; Han et al., 1996; Porter et al., 2001; Song et al., 2014), Russia, Ukraine, and Azerbaijan (Maher et al., 2003; Maher and Thompson, 1995; Alekseeva et al., 2007), United States (Geiss and Zanner, 2007; Geiss et al., 2008), England (Dearing et al., 1996), and Spain (Torrent et al., 2010). Analyzing the same phenomenon at the BLP, where the parent material variation is minimal, will help to determine the general climatic factors that cause χ variability across this specific region.

2. Material and methods

2.1. Sampling strategy

Surface soils were sampled between July and October 2011, in association with the soil fertility monitoring program of the Institute of Field and Vegetable Crops, Novi Sad. The network of samples was distributed uniformly across the BLP (Fig. 1), as in previous investigations by the Institute of Field and Vegetable Crops of Novi Sad (e.g. Ninkov et al., 2017), with one sample for each 4 km^2. In this study, we collected 178 soil samples of different soil types from the BLP, among which 50 samples used in this study represent the chernozem soil type (Supplementary Fig. 1, Supplementary Table 1). Those samples have been excluded from zones of intensive industry and traffic, settlements, gullies, and freshwater ecosystems located on the plateau, which can seriously affect pedogenesis. The depth from which the samples were taken is 10 cm.

All samples were air dried and carefully sieved to 2 mm. The samples were then prepared for magnetic measurements in the laboratory for paleo- and environmental magnetism, University of Bayreuth, Germany.

2.2. Magnetic measurements

In the laboratory for paleo- and environmental magnetism at the University of Bayreuth, Germany, environmental magnetic measurements were undertaken on the air dried soil samples. Samples were placed in non-magnetic plastic boxes (vol. 6.4 cm^3), carefully compressed with a non-magnetic pistil, and - before closing the lid - fixed with compressed cotton wool to prevent movement during measurement. Magnetic volume susceptibility, κ, was then determined with a susceptibility bridge (VFSM; Magnon, Germany) at AC-fields of 320 Am^{-1} at frequencies of 310 Hz and 3013 Hz, respectively.

Magnetic susceptibility is defined as the ratio of induced magnetization (in Am^{-1}) to the inducing magnetic field (generated as alternating magnetic field in the coil of a "susceptibility bridge" and also given in Am^{-1}) Therefore it is a dimensionless variable and is reported in units of the SI (*Système international* (*d'unités*)) unit system (Evans and Heller, 2003). Because magnetic susceptibility is a physical quantity which is first of all volume-related, all susceptibility bridges are set to a standard volume (in most cases $1 \times 10^{-6}\,m^3$), thus, "expecting" the measured samples to have a specific volume. For any differing volume, a correction factor has to be applied to get the volume susceptibility (κ). As the amount of the material measured plays a crucial role, κ is normalized by the density (in kg/m^3) of the sample and, thus, given as mass specific susceptibility, χ, (in m^3/kg), reflecting mainly the concentration of para- and ferromagnetic minerals as well as their magnetic grain size variations (domain configuration (Maher, 2011)).

It is important to note that pedogenetically formed, extremely fine-grained superparamagnetic (SP) ferrimagnetica (< 0.03 μm) minerals have a 2- to 3-times higher χ values, than larger magnetic particles (single domain (SD, Pseudo-SD; ~0.03–10.00 μm, and multi-domain ferrimagnetica (MD, > 10 μm)) do. The frequency dependence of susceptibility, χ_{fd}, is a thus measure for the relative contribution of SP-ferrimagnetica minerals, close to the SP-SD threshold, and is generally applied as proxy for the exclusively pedogenetically formed fraction of ferrimagnetica minerals (Liu et al., 2012; Buggle et al., 2014):

$$\chi_{fd}(\%) = \{[\chi(310\cdot\mathrm{Hz}) - \chi(3000\cdot\mathrm{Hz})]/\chi(310\cdot\mathrm{Hz})\} \times 100$$

Beside, χ_{fd} is also determined as:

$$\chi\Delta = (\chi 1f - \chi hf)$$

This difference, χΔ, between χlf (low frequency magnetic susceptibility) and χhf (high frequency magnetic susceptibility), is used to determine the detrital background susceptibility of the unweathered parent loess (Forster et al., 1994; Buggle et al., 2014; Zeeden et al., 2016). It should also be noted that the magnetic susceptibility values may change based on grain size changes of the magnetic particles, and not due to their variation in total concentration of specific minerals (Liu et al., 2012).

2.3. Meteorological data

In order to correlate magnetic data from surface soils to climate, we used two most important climatic parameters; temperature and precipitation, and climate index of aridity, all from 32 meteorological stations on and near the BLP (Fig. 2, Supplementary Table 2). Altitudes of all meteorological stations range between 81 m and 102 m above mean sea level. Only stations that have continuous data sets for the period 1946–2006 were selected. Data sets of temperature and precipitation were downloaded (http://www.hidmet.gov.rs/19.01.2018) from 6 and 30 meteorological stations, respectively. Stations where the temperature was not measured received the temperature data by interpolation from the stations which had temperature measurement. The stations are operated by the Republic Hydrometeorological Service of Serbia.

Mean annual temperature (MAT) and mean annual precipitation (MAP) for meteorological stations were calculated in *Excel* spreadsheets and used to calculate the annual De Martonne aridity index (I_{DM}) by following equation:

$$I_{DM} = MAP/(MAT + 10),$$

where MAT are presented in °C and for MAP in mm (De Martonne, 1925). This index has previously been used for determining aridity in the Vojvodina (Hrnjak et al., 2014) and Central Serbia (Radaković et al., 2017 in press).

Optically stimulated luminescence of the loess on the Crvenka LPS (Marković et al., 2018 in press) shows that the landscape stabilized and soil formation began at the onset of the Holocene (Stevens et al., 2011). Although the period of climatic measurements is short in comparison to the soil forming interval, we assume that the trend of MAP and MAT was quasi constant.

2.4. Mapping and statistical analysis

The margins of the BLP are not always easily recognized on the field. In this study, we defined them by using a digital elevation model, topographic maps, and a soil map of the Vojvodina. These data sets were combined and examined in *ArcMap 10.1*. Within the GIS, the coordinates of the soil samples were imported, each with its unique χ and χ_{fd} values. Both the meteorological and the soil data were examined spatially using ordinary Kriging, and mapped using isotherms and isohyets for the meteorological data and as isolines for I_{DM}. These isolines were then overlapped onto the interpolated χ and χ_{fd} values.

In order to determine the function which best fits the data, we fit the data to trigonometric, exponential, and polynomial functions (first, second, third, and fourth order) in *MatLab*. The R^2 (Coefficient of Determination) and RMSE (Root Mean Square Error) values were determined for all the functions. The fourth order polynomial function gave the best results, and is presented in this paper. Pearson (1920) correlation coefficients and Spearman (1904) rank correlations were also determined.

3. Results

3.1. Magnetic properties of surface soils

Fig. 3A represents the interpolated values of χ from 50 soil samples, where dark blue colors imply higher values of rock magnetic parameters and therefore stronger magnetic enhancement. Soil magnetic values for χ vary from 0.66 to 1.74 ($\times 10^{-6}\,m^3/kg$), with an average value of $1.2 \times 10^{-6}\,m^3/kg$. Data mapped in Fig. 3A shows a general enhancement in χ values in the central, southern and western sections of the BLP. The magnetic signal gradually decreases to the northeastern part of the BLP, where it reaches the lowest values. χ_{fd} values exhibit a similar pattern to those of χ (Fig. 3B). Most of the BLP surface soils have values of χ_{fd} that exceed 12.2%, with higher values in the southern and the western parts of the plateau. Values > 13.0% exist only in the southern half of the BLP, whereas low values are found in the northeastern part of the region. One isolated spot with lower value than its surrounding can be seen at the west of the plateau, just like one in the previous figure. Lower values are also present on the same latitude but at the center of BLP. The drop in values of χ_{fd} from southwest to northeast on this map is more sudden than for χ (compare Fig. 3A and B).

Fig. 2. Spatial distribution of meteorological stations in Vojvodina used in this study.

In Fig. 4, the frequency dependent susceptibility is expressed as $\chi\Delta$ ($\chi\Delta = \chi(310)$-$\chi(3000)$ in m^3/kg), and given as function of $\chi(310)$ Hz, indicating the "true loess line" as suggested by Zeeden et al. (2016) and based on Forster et al. (1994). The topsoil samples from the BLP group well to the recent and fossil topsoil samples from the Semlac section in the Romanian Banat (c. 150 km east of the BLP), indicating similar magnetic enhancement processes and background magnetic susceptibilities in the parent loess.

3.2. Statistical relationships between soil magnetic properties and climatic parameters

3.2.1. Relationship between χ and MAP, MAT, and I_{DM}

Mean annual precipitation totals on the BLP vary between 530 mm and 590 mm. Isohyets with the value of 590 mm are present at the south and west of the plateau. The value decreases towards northeast where it shows 530 mm. This general direction of isohyets is similar to the isohyets of the whole Vojvodina region, due to western winds (Tošić et al., 2018) which bring moisture (Tošić et al., 2014). Lower precipitation values can be seen at the west in an isolated spot, where the χ is also reduced.

The fourth order polynomial function applied on the data from this paper gives the largest R^2 value. The same function is used on the Chinese Loess Plateau (Song et al., 2014). Fourth order polynomial function between the χ and precipitation variables is shown in Fig. 5A. This function has a R^2 value of 0.57. Other function fits between the same parameters are presented in Supplementary Fig. 2.

The MAT for Vojvodina region is 11.1 °C for the period from 1949 to 2006 (Hrnjak et al., 2014). The MAT for the past 60 years at BLP ranged from 10.9 °C to 11.2 °C. The low amount of variation can be explained by the small size of the BLP. The exact relationship between the MAT and χ cannot be clearly recognized on the map (Fig. 5B). The same fourth order polynomial function used for χ and MAT, shows the R^2 value of 0.34 (Fig. 5B). Supplementary Fig. 3 shows other fits between the same parameters.

Humid climate covers 75% of Vojvodina (Hrnjak et al., 2014). Precipitation and temperature data for the past 6 decades illustrate that the climate of Vojvodina is semi-humid and humid in most of the years. During the summer, the entire BLP has an arid climate (Hrnjak et al., 2014). De Martonne (1925) used the value 28 of I_{DM} to distinguish semi humid from humid climate. The line with this value (28) separates southwestern from northeastern part of the plateau (Fig. 5C). The R^2 value between χ and I_{DM} is 0.64. Other R^2 and RMSE values of the different functions fit can be found in Supplementary Fig. 4.

In conclusion, aridity has the highest correlation with χ, followed by MAP, and then the MAT.

3.2.2. Relationships among χ_{fd} and MAP, MAT, and I_{DM}

The values of MAP and χ_{fd} show a similar trend, they decrease in the same direction. Samples with χ_{fd} values between 4% and 7% have MAP values around 535 mm. The fourth order regression function for these parameters has the value of $R^2 = 0.71$. Supplementary Fig. 5 shows other function fits between MAP and $\chi_{fd.}$ If the MAP was the crucial factor for variability of χ_{fd} values, we could expect low χ_{fd} signal of samples at eastern part of the BLP. On the other side, the location of these samples has one of the highest MATs on the BLP (above 11.0 °C). Another deviation can be seen at the most western and northern part of the BLP. Both areas have the same isotherm (10.9 °C) but the values of χ_{fd} are clearly different: from the lowest of 4.30% to the 13.28%. The R^2 from data plotted in Fig. 6B is 0.21, and it is the lowest of all calculated in this study. Function fits of MAT and χ_{fd} can be found in Supplementary Fig. 6. The more humid area of the plateau corresponds to the higher values of χ_{fd}. Again, there is an area of I_{DM} with the value of 25.5 on the east of the BLP which cannot be associated with high values of χ_{fd}. This is the consequence of the interpolation of high MAT measured at Senta meteorological station, which is the part of equation for $I_{DM.}$ The function on Fig. 6C shows the R^2 value of 0.46, and other R^2 and RMSE values are presented in Supplementary Fig. 7.

The Pearson and Spearman's correlation of all the parameters above is given in Table 1. Magnetic susceptibility (χ) has the highest correlation coefficient with the aridity of the BLP, however the MAP is also an important factor. MAP has the strongest influence on χ_{fd}, although the I_{DM} is very close.

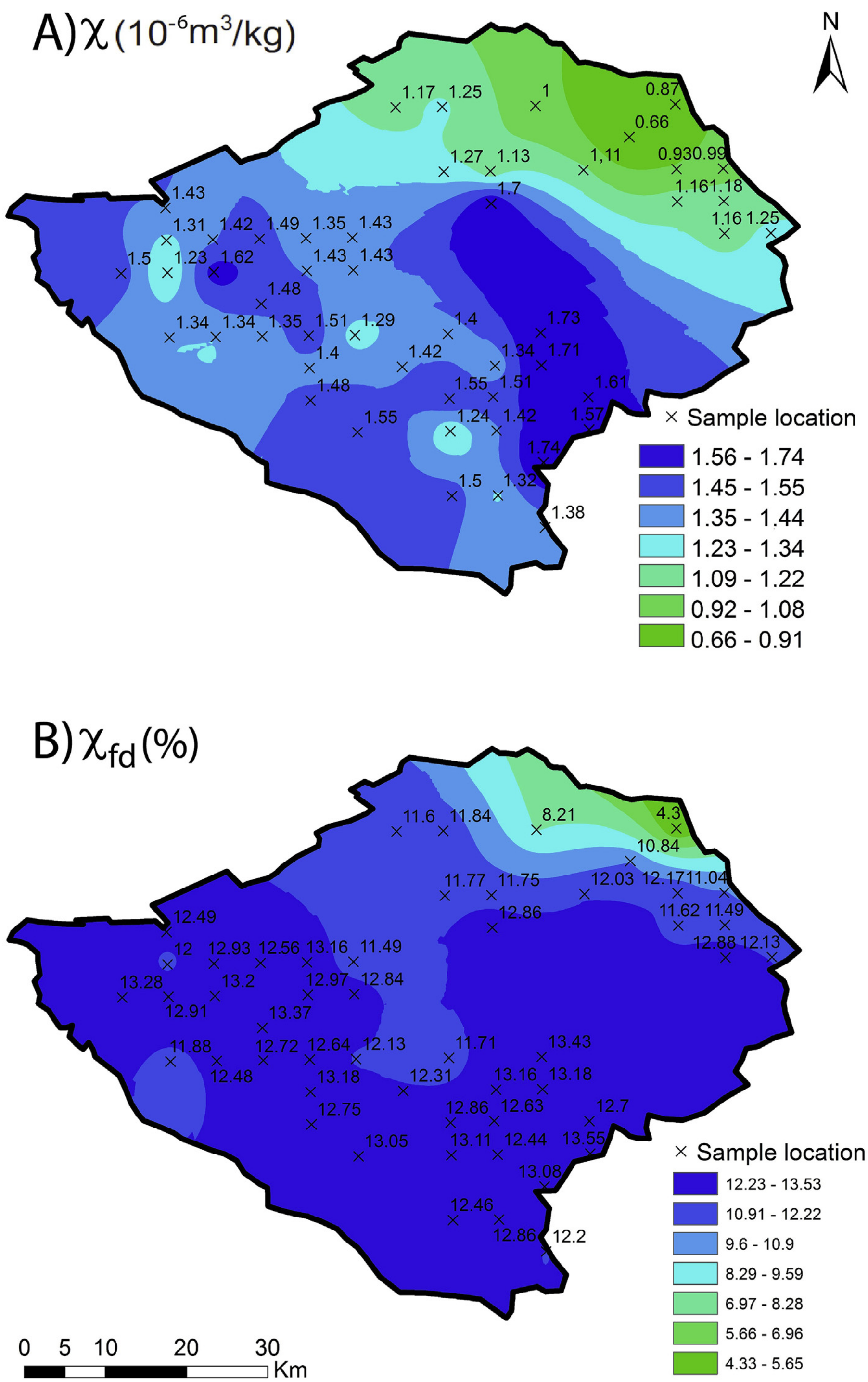

Fig. 3. Soil magnetic data for the Bačka Loess Plateau. (A) values of χ ($\times 10^{-6}$ m^3/kg) and (B) values of χ_{fd} (%).

4. Discussion

The long-term temperature, precipitation and aridity of the Vojvodina region have been examined in previous studies (Hrnjak et al., 2014; Tošić et al., 2014, Gavrilov et al., 2015, 2016). This data has not been compared to magnetic properties of the soils before, although the formation of chernozem is dominated by these climatic factors. Our data shows that MAP and I_{DM} are positively correlated with χ and χ_{fd} values of the modern soils. Similar correlations have also been reported for loess and soils on the Chinese Loess Plateau (CLP), (Han et al., 1996; Maher and Thompson, 1995; Guo et al., 2011; Song et al., 2014). Consistent with the here presented data from the BLP, MAP on the CLP also has a stronger correlation than MAT (Song et al., 2014; Liu et al., 2017). Two samples on the north of the BLP stand out with the lower values of χ_{fd}, due to different variety of chernozem (Supplementary Figs. 8, 9, 10, and 11). The development of magnetic signals in silty soils is similar on both plateaus, because the quartz is iron deficient (Maher and Thompson, 1995). Similar data on soils spread between the Caspian Sea to the North Caucasus Mountains illustrate that precipitation has the strongest correlation with the magnetic signal, with

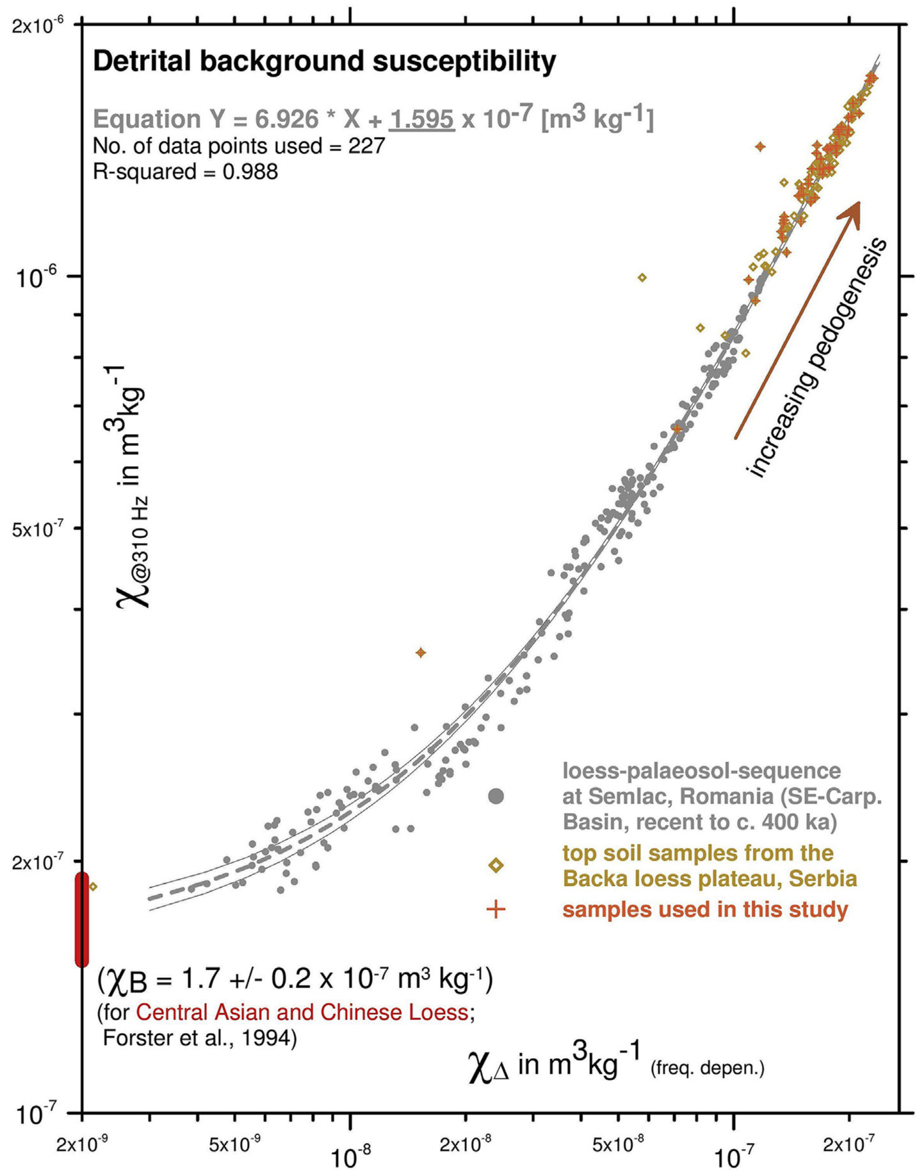

Fig. 4. Low frequency susceptibility χ(310 Hz) in m^3/kg vs. frequency dependent susceptibility (χ_{fd} (310 Hz)-χ_{fd} (3000 Hz) in m^3/kg) from the 50 samples used in the study, and data from Semlac, Romania (Zeeden et al., 2016). All samples follow a clear trend showing increasing χ with increasing χ_{fd}.

an R^2 of 0.93 (Maher et al., 2002; 2003; Alekseeva et al., 2007). Under tropical circumstances MAP is also the dominant factor that influences χ, rather than MAT (Balsam et al., 2011).

The modern soil of the CLP has the χ values between 0.12 and 2.00 ($\times 10^{-6}$ m^3/kg) (Song et al., 2014). These values are similar to values from the BLP (0.66–1.74 $\times 10^{-6}$ m^3/kg), especially when it is considered that the CLP is more than 250 times as extensive. Xia et al. (2012) analyzed surface soil samples from the Gobi area, and obtained χ values between 0.26 and 0.93 ($\times 10^{-6}$ m^3/kg), and χ_{fd} values between 1.4% and 14.4%. The Pearson correlation coefficient for the BLP shows that MAP has the most dominant effect on χ_{fd}, as it is the case for the previously mentioned studies (Xia et al., 2012; Song et al., 2014). The correlation coefficients of MAT, MAP and χ, χ_{fd} of the CLP, and MAT, MAP, IDM and χ, χ_{fd} of the BLP are shown in Table 2. Hence, the aridity index is the most strongly correlated to χ values on the BLP. The aridity index was never correlated to χ on the CLP top soil, but latest research show that MAP is the most closely associated with χ on the CLP (Table 2).

In an attempt to place our data into a wider context, we plotted χ values for modern soils of the northern hemisphere vs. MAP data for those same soils (Song et al., 2014, Fig. 7B). Liu et al. (2017) determined that the pedogenic production of magnetic minerals is limited for sites where MAP is less than ≈340 mm. Data from Hainan Island, located in the tropical south of China, appear to show decreasing χ with increasing MAP, suggesting that increases in magnetic signal with MAP are mainly associated with sites where the MAP remains below ~1200 mm (Balsam et al., 2011). The BLP is located in the temperate climate zone, and has the average MAP from 530 mm to 590 mm. MAP from the BLP is between these limits, which is why the trend line of BLP fits well within all other studies (Fig. 7(A and B)). The results from this study and data from the literature provide a consistent trend of χ variations with precipitation.

5. Conclusion

In this study χ and χ_{fd} were determined for 50 surface soil samples

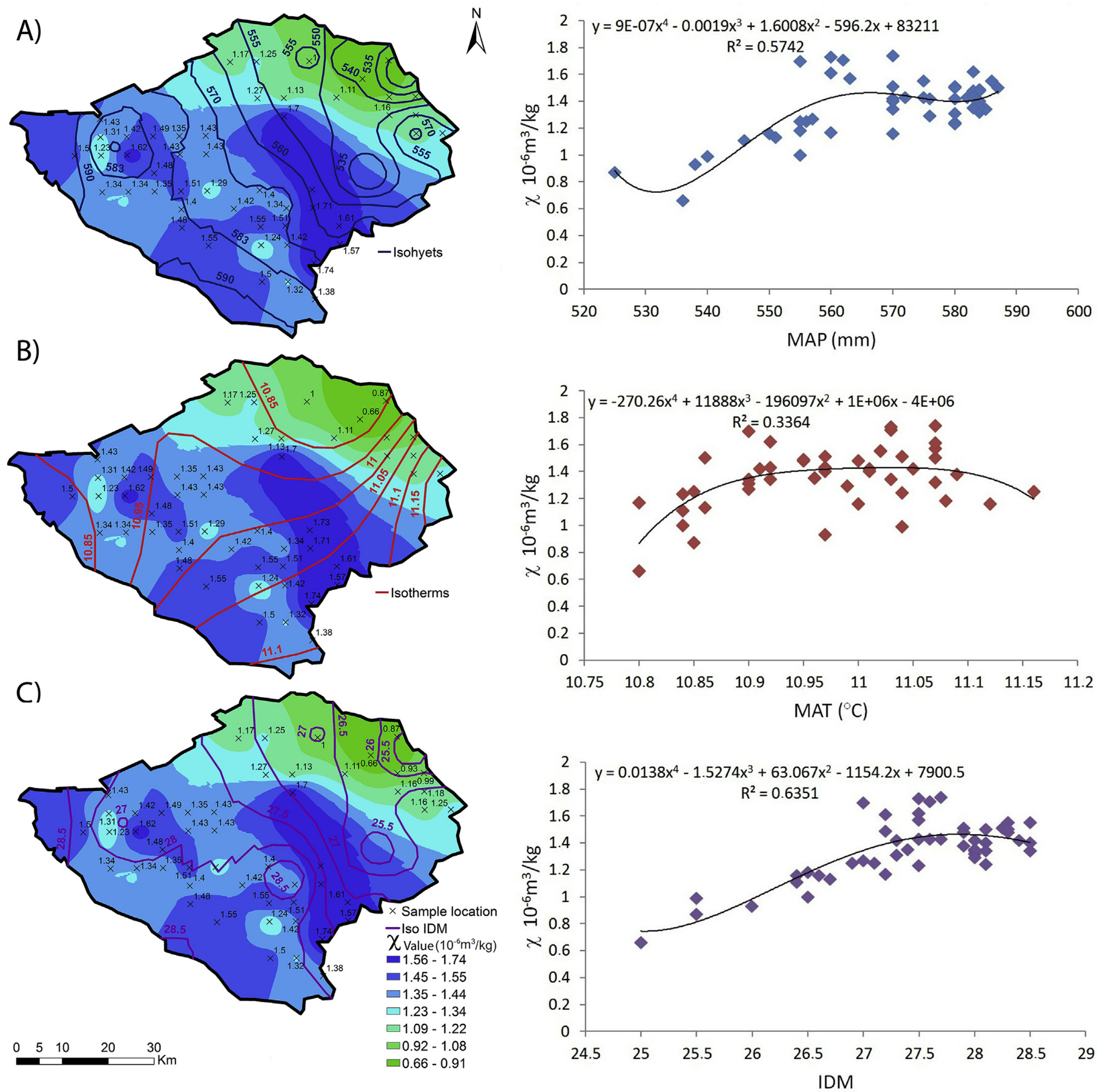

Fig. 5. Data interpolated by Kriging of χ ($\times 10^{-6}$ m^3/kg) and (A) mean annual precipitation (mm), (B) mean annual temperature (°C), and (C) De Martonne aridity index values for the BLP, for the period 1946–2006. Right panel represents the values of every sample plotted on scatter, with fourth polynomial order.

(chernozem type) across the Bačka Loess Plateau. These values were then statistically compared to MAP, MAT, and I_{DM}, using interpolated values of meteorological data for the past 60 years. The relationships between local climatic conditions and magnetic properties of the modern soils for the BLP were established statistically, and are following:

(1) χ values decrease generally from the south, west and center of the BLP to the north and east. Overall, χ values range from 0.6–1.74 × 10^{-6} m^3/kg.
(2) Most soils on the BLP have χ_{fd} values > 11%, reaching 13.5% in some areas; the northeastern part of the region has the lowest value (4.3%).
(3) MAP correlates best with χ_{fd} (0.60), which suggests that mean annual precipitation is the most important factor for different χ_{fd} values across the plateau.
(4) I_{DM} and χ data show high correlation of 0.71, but MAP and χ also showed a positive (0.59) correlation. These correlations are best explained by the aridity index, which is partially derived from the precipitation. Both parameters can be considered to be drivers of the χ values for the loess on the BLP.

Statistically derived relationships between climatic conditions and magnetic properties of soils on the BLP are similar to those derived for the CLP. Thus, our study established the similarity between the Serbian and Chinese loess plateaus, despite being located on different sides of

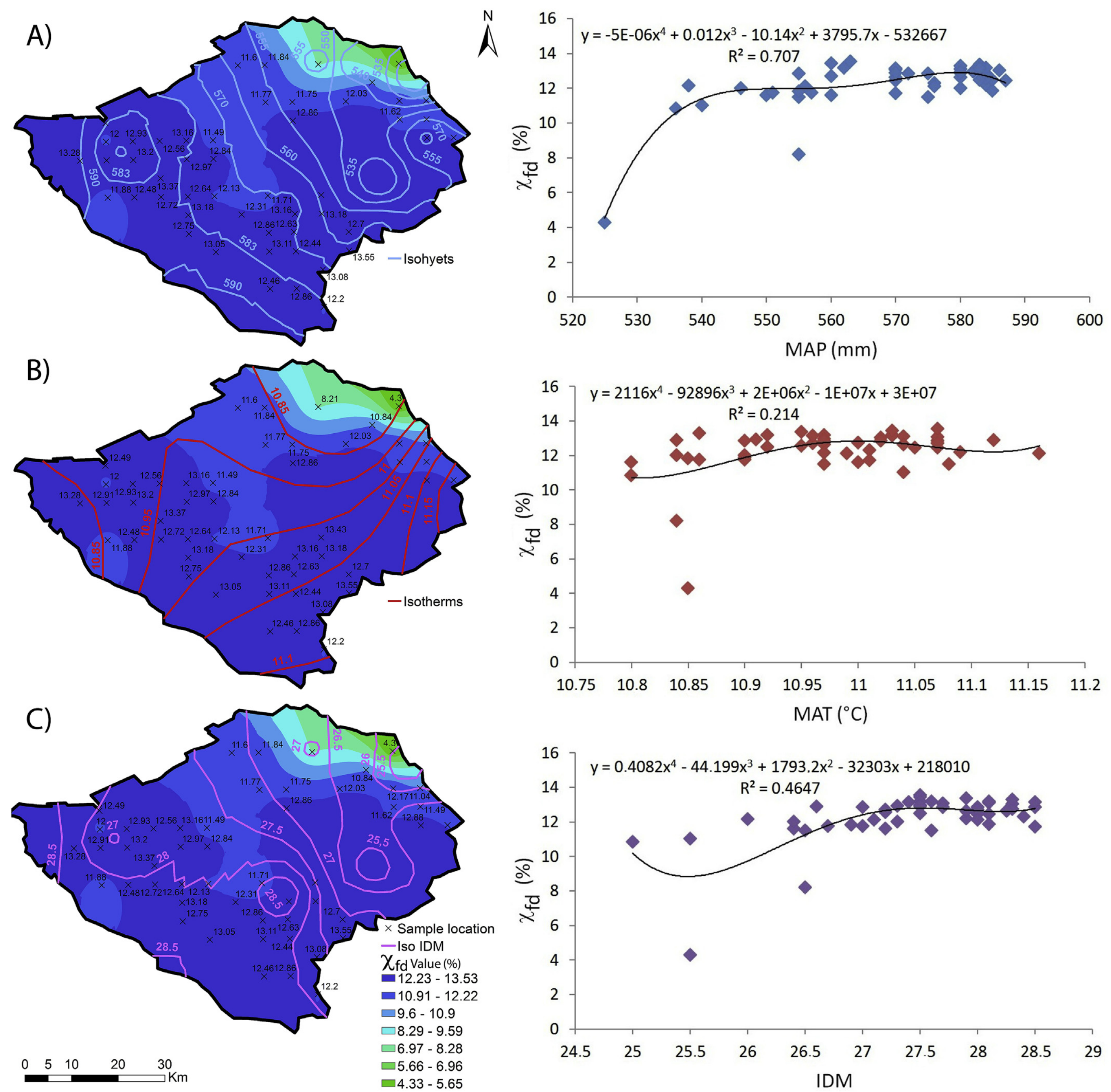

Fig. 6. Data interpolated by Kriging of χ_{fd} (%) and (A) mean annual precipitation (mm), (B) mean annual temperature (°C), and (C) De Martonne aridity index values for the BLP, for the period 1946–2006. Right panel represents the values of every sample plotted on scatter, with fourth polynomial function equations.

Table 1
Pearson correlation coefficients and Spearman's rank correlation between climatic parameters, I_{DM}, χ and χfd on the BLP; bold values represent the highest correlations for χ and χ_{fd}.

	χ_MAP	χ_MAT	χ_IDM	χ_{fd}_MAP	χ_{fd}_MAT	χ_{fd}_IDM
Pearson	0.59	0.38	**0.71**	**0.6**	0.36	0.57
Spearman	0.41	0.32	**0.53**	0.45	0.27	**0.46**

Table 2
Pearson correlation coefficients among the χ, χ_{fd}, and following variables: MAP, MAT on CLP (Song et al., 2014), and MAP, MAT, and I_{DM} on BLP.

Chinese Loess Plateau	χ	χ_{fd}	Bačka Loess Plateau	χ	χ_{fd}
MAP	0.79	0.79	MAP	0.59	0.60
MAT	0.76	0.77	MAT	0.38	0.36
			I_{DM}	0.71	0.57

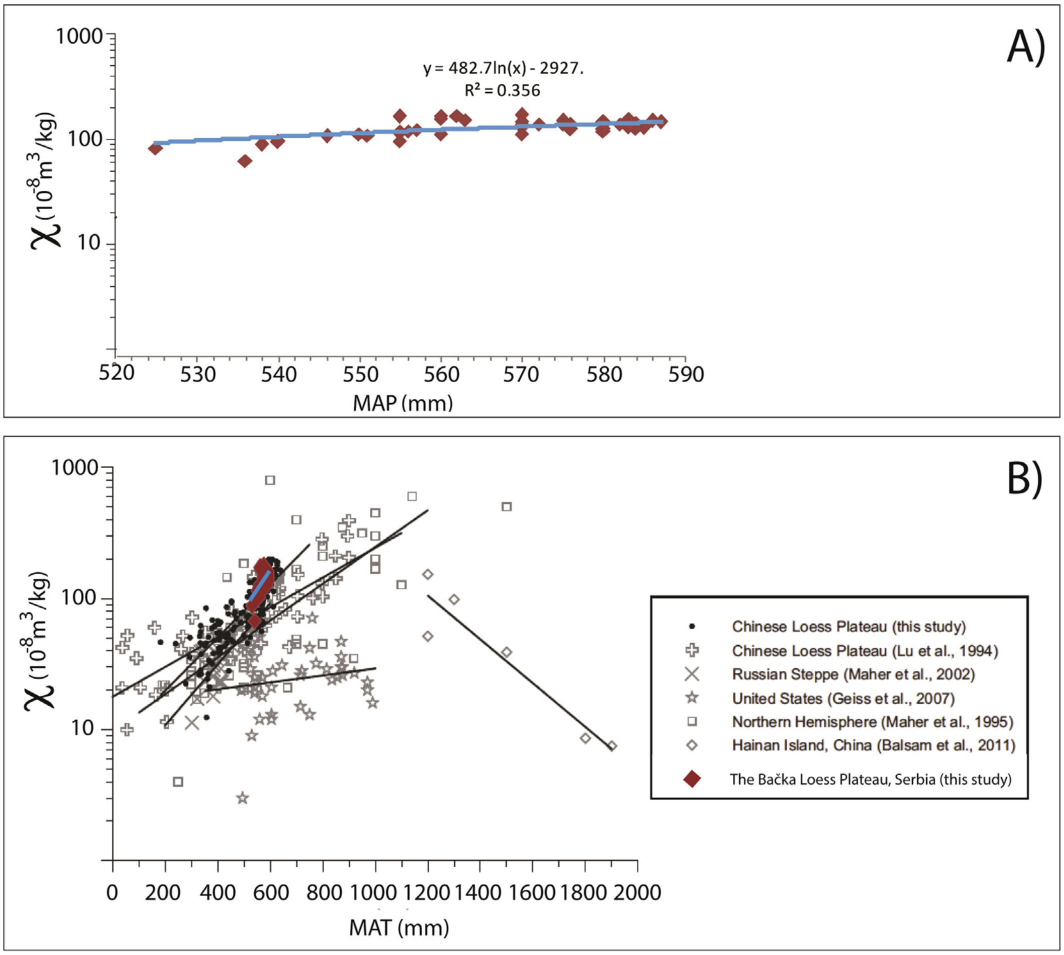

Fig. 7. (A) semi-logarithmic plot of modern soil magnetic susceptibility ($\times 10^{-8}$ m^3/kg) vs. MAP (mm) on the BLP and (B) same plot with other studies from Northern Hemisphere including the data from this study (BLP is presented with blue logarithmic trendline, red samples, in unit $\times 10^{-8}$ m^3/kg). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the Eurasian continent. The presented study is the first utilizing the De Martonne aridity index as a climatic proxy for explaining the magnetic susceptibility pattern in soils developed in loess; this index resulted in high spatial correlation coefficients between χ and I_{DM}.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2018.04.040.

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